# Effect of Out-of-Band Response in *NOAA-16* AVHRR Channel 3b on Top-of-Atmosphere Radiances Calculated with the Community Radiative Transfer Model

QUANHUA LIU,* XINGMING LIANG,+ YONG HAN,# PAUL VAN DELST,@ YONG CHEN,&
ALEXANDER IGNATOV,** AND FUZHONG WENG**

** Joint Center for Satellite Data Assimilation, and Perot Government Systems, Camp Springs, Maryland*
*+ NOAA/NESDIS Center for Applications and Research, Camp Springs, Maryland, and Cooperative Institute for Research in the Atmosphere, Colorado State University, Fort Collins, Colorado*
*# Joint Center for Satellite Data Assimilation, and NOAA/NESDIS Center for Applications and Research, Camp Springs, Maryland*
*@ Joint Center for Satellite Data Assimilation, Camp Springs, Maryland*
*& Joint Center for Satellite Data Assimilation, Camp Springs, Maryland, and Cooperative Institute for Research in the Atmosphere, Colorado State University, Fort Collins, Colorado*
*** NOAA/NESDIS Center for Applications and Research, Camp Springs, Maryland*

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ABSTRACT

The Community Radiative Transfer Model (CRTM) developed at the Joint Center for Satellite Data Assimilation (JCSDA) is used in conjunction with a daily sea surface temperature (SST) and the National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) atmospheric data and surface wind to calculate clear-sky top-of-atmosphere (TOA) brightness temperatures (BTs) in three Advanced Very High Resolution Radiometer (AVHRR) thermal infrared channels over global oceans. CRTM calculations are routinely performed by the sea surface temperature team for four AVHRR instruments on board the National Oceanic and Atmospheric Administration (NOAA) satellites *NOAA-16*, *NOAA-17*, and *NOAA-18* and the Meteorological Operation (MetOp) satellite *MetOp-A*, and they are compared with clear-sky TOA BTs produced by the operational AVHRR Clear-Sky Processor for Oceans (ACSPO). It was observed that the model minus observation (M−O) bias in the *NOAA-16* AVHRR channel 3b (Ch3b) centered at 3.7 $\mu$m experienced a discontinuity of ~0.3 K when a new CRTM version 1.1 (v.1.1) was implemented in ACSPO processing in September 2008. No anomalies occurred in any other AVHRR channel or for any other platform. This study shows that this discontinuity is caused by the out-of-band response in *NOAA-16* AVHRR Ch3b and by using a single layer to the NCEP GFS temperature profiles above 10 hPa for the alpha version of CRTM. The problem has been solved in CRTM v.1.1, which uses one of the six standard atmospheres to fill in the missing data above the top pressure level in the input NCEP GFS data. It is found that, because of the out-of-band response, the *NOAA-16* AVHRR Ch3b has sensitivity to atmospheric temperature at high altitudes. This analysis also helped to resolve another anomaly in the absorption bands of the High Resolution Infrared Radiation Sounder (HIRS) sensor, whose radiances and Jacobians were affected to a much greater extent by this CRTM inconsistency.

## 1. Introduction

The Community Radiative Transfer Model (CRTM) is a sensor-band-based fast radiative transfer model developed at the Joint Center for Satellite Data Assimilation (JCSDA; Han et al. 2006). It is a key component in the U.S. data assimilation for weather forecasting at the National Centers for Environmental Prediction (NCEP) of the National Oceanic and Atmospheric Administration (NOAA). It is used in conjunction with the atmospheric and surface data from users of many applications, including infrared (IR) and microwave satellite radiance inversions for atmospheric and surface parameters as well as data assimilation (Liu and Weng 2006). Accuracy of the CRTM forward calculations and derivatives with respect to the surface and atmospheric parameters (Jacobians) is critically important for these applications. The CRTM has

*Corresponding author address:* Quanhua Liu, Joint Center for Satellite Data Assimilation, 5200 Auth Road, Room 7042, Camp Springs, MD 20746.
E-mail: quanhua.liu@noaa.gov

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been implemented in the following: the NOAA/NCEP data assimilation system for supporting weather forecasting; the NOAA/NCEP and the National Aeronautics and Space Administration (NASA) Global Modeling and Assimilation Office (GMAO) for reanalysis; the Weather Research and Forecasting (WRF) model for radiance assimilation; the NOAA Microwave Integrated Retrieval System (MIRS) for operational products; and other institutions and companies.

There are various requirements on radiative transfer calculation accuracy and precision, depending on application purposes and sensor characteristics. For the Advanced Very High Resolution Radiometer (AVHRR) infrared channel to the sea surface temperature (SST) application, the brightness temperature (BT) simulation precision is better than 0.05 K, which is generally acceptable because it is smaller than the AVHRR three-channel noise equivalent temperature. The simulation accuracy for the AVHRR infrared channel is better than 0.01 K in comparison to detailed line-by-line calculations. The SST team at the NOAA National Environmental Satellite, Data, and Information Service (NESDIS) is one of the major users of the CRTM. Recently, a Web-based Monitoring of IR Clear-Sky Radiances over Oceans for SST (MICROS; data available online at http://www.star.nesdis.noaa.gov/sod/sst/micros/) system has been established (Liang et al. 2009a) to validate AVHRR BTs over clear-sky ocean. The MICROS system helpfully complements the simultaneous nadir overpass (SNO) method by Cao et al. (2004). In particular, it proved uniquely useful in the shortwave part of the infrared atmospheric window. AVHRR channel 3b centered at 3.7 $\mu$m is the most transparent IR band of AVHRR, and it is instrumental for SST retrievals and radiance assimilation at night.

However, BTs in this spectral interval are extremely challenging to validate with the SNO technique, which uses data at high latitudes where the measured radiances and BT can be very low. For example, Planck radiance (Liou 1992) at BT $\sim$ 250 K is only $\sim$0.053 mW m$^2$ sr cm$^{-1}$, 12 times smaller than that at BT $\sim$ 300 K. As a result, the SNO signal at 3.7 $\mu$m may be comparable to noise at a very cold temperature, which may render it unusable for quantitative analyses. Moreover, the shortwave IR may be contaminated by solar reflection during the polar day. The calibration of AVHRR channel 3b may not be reliable in the terminator zone (Cao et al. 2001).

The CRTM development is closely tied to the broad applications and needs of users. The CRTM team works closely with users to understand their applications and satisfy their new requirements. One of the issues reported by the SST team to the CRTM team was an abnormal model minus observation (M$-$O) bias in the *NOAA-16* AVHRR 3b (Liang et al. 2009a). Special analysis jointly performed by the CRTM and SST teams has shown that this was due to the out-of-band response in this channel and the way the atmospheric and surface inputs were handled in the alpha version of CRTM initially used by the SST team. In the following section, we quantitatively analyze the effect of out-of-band response on CRTM calculations.

## 2. Results

Since July 2008, the MICROS system has routinely monitored the M$-$O biases in AVHRR IR bands on board *NOAA-16*, *NOAA-17*, *NOAA-18*, and the Meteorological Operation (MetOp) satellite *MetOp-A*. Once a day, the results for the previous day are automatically calculated and updated (available online at http://www.star.nesdis.noaa.gov/sod/sst/micros/). More details about the MICROS system can be found in (Liang et al. 2009b).

Figure 1 shows the nighttime time series in AVHRR channel 3b as it appears on the MICROS Web page. In July–August 2008, when the alpha version of CRTM was still in use in the AVHRR Clear-Sky Processor for Oceans (ACSPO) processing, the M$-$O bias for *NOAA-16* was $\sim$0.3 K cooler than the three other satellites, which formed a tight cluster. However, when the new CRTM version 1.1 (v.1.1) was implemented in ACSPO on 4 September 2008, the *NOAA-16* M$-$O bias was significantly reduced and became consistent with *NOAA-17*, *NOAA-18*, and *MetOp-A*. Interestingly, the M$-$O bias for the three latter sensors did not respond to the CRTM upgrade. The warm M$-$O bias of about +0.2 K, now consistent for all platforms, may be due in part to the aerosol absorption and scattering (which has not been included in the CRTM calculations for this study) and in part to the use of bulk Reynolds et al. (2007) SST in CRTM. A more appropriate input in CRTM would be skin SST, which may be several tenths of a kelvin cooler than the bulk SST (Donlon et al. 2002). In this study, aerosols have not been taken into account for the CRTM calculation. The CRTM-calculated brightness temperature may be overestimated by the neglect of aerosols. Uncertainties in the atmospheric water vapor profile may also result in a relatively large error in the brightness temperature calculation. Error in surface emissivity for the large satellite viewing angle needs to be investigated.

To understand the change in the CRTM BTs that occurred on 4 September 2008, we may notice that the top pressure in the NCEP Global Forecast System (GFS) data used in CRTM is specified at 10 hPa (data available online at http://www.emc.ncep.noaa.gov/modelinfo/). If

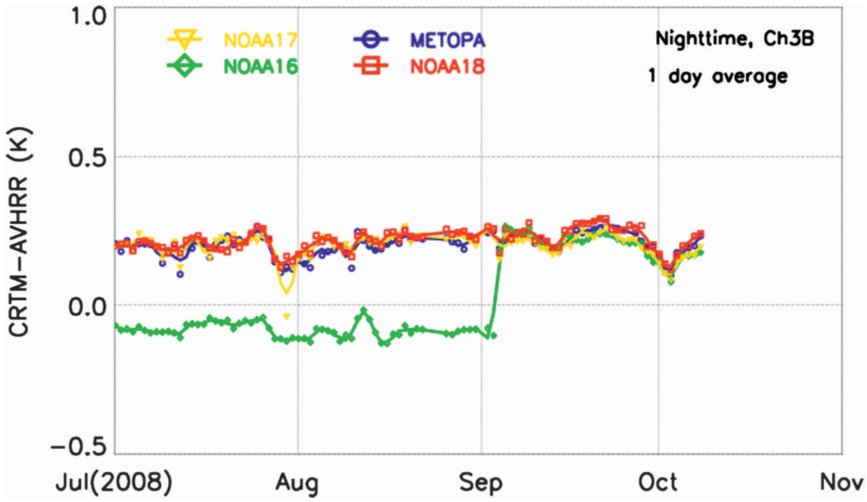


FIG. 1. The M−O (CRTM BT minus ACSPO BT) in AVHRR channel 3b of *NOAA-16*, *NOAA-17*, *NOAA-18*, and *MetOp-A* during nighttime. Data are from the MICROS Web site.

the input top pressure is larger than 0.005 hPa, then the CRTM alpha version resets it to the default pressure of 0.005 hPa. The atmosphere between 0.005 and 10 hPa is then designated as one top layer, and its temperature, water vapor, and ozone are uniformly specified from the respective GFS 10-hPa values. As a result, atmospheric absorption may be somewhat inflated in this top layer. The mechanism of absorption line broadening is changed from molecular collision (Lorentz line shape) at 10 hPa to molecular motion (Doppler line shape) above 0.1 hPa. The recently released CRTM version 1.1 attempted to solve this problem by filling in the space above 10 hPa from one of the standard World Meteorological Organization (WMO) atmospheres (specified by the user) with many sublayers. The standard profiles of the temperature, water vapor, and ozone above 10 hPa are used and uniformly shifted to match the respective GFS 10-hPa values.

Figure 2 plots the spectral response functions (SRFs) of AVHRR channel 3b for *NOAA-16* (solid line), *NOAA-17* (dashed line), *NOAA-18* (dotted line), and *MetOp-A* (dashed–dotted line). The data are available from the NOAA Web site (available online at http://www.star.nesdis.noaa.gov/smcd/spb/fwu/solar_cal/spec_resp_func/index.html). All SRFs are located in the window region and outside absorption bands, except for *NOAA-16* whose channel 3b has a significant out-of-band leakage centered at ~2360 $cm^{-1}$ (~4.24 $\mu$m), the center of a strong $CO_2$ absorption band. Figure 3 displays the gaseous absorption line strengths, further revealing the strong $CO_2$ absorption near the peak of the out-of-band response [SpectralCalc.com (available online at http://www.spectralcalc.com) provided a Web tool using High Resolution Transmission (HITRAN) Molecular Absorption Database 2004 data (Rothman et al. 2005)]. The main absorbers for the spectral region between 2200 and 3200 $cm^{-1}$ are carbon dioxide, water vapor, and ozone. In the spectral region, the total column water vapor absorption is usually stronger than the total column ozone absorption because water vapor amount is generally larger than ozone amount. The black curve superimposed in Fig. 2 is atmospheric transmittance from 0.005 to 20 hPa. The peak of the weighting function for the out-of-band part of the SRF is located at 17 hPa, and there is significant absorption above 10 hPa. Figure 2 also shows that the absorption above 20 hPa for *NOAA-17*, *NOAA-18*, and *MetOp-A* AVHRR channel 3b is negligible.

Figure 4 shows that the absorption coefficients above 10 hPa for *NOAA-16* AVHRR channel 3b strongly depend on the atmospheric pressure. Treating the atmosphere above 10 hPa as one layer may cause a large uncertainty in transmittance and in its Jacobian calculations resulting from the higher nonlinearity. Because of the strong $CO_2$ absorption near the peak of the out-of-band response from *NOAA-16* AVHRR channel 3b, lifting the users' top pressure from 10 hPa to the CRTM model top pressure of 0.005 hPa for the CRTM alpha version results in a significant error in simulations. The lifting in the CRTM alpha version does not cause significant error to channel 3b for *NOAA-17*, *NOAA-18*, and *MetOp-A*, because the optical depth above 10 hPa is negligible, unless there is an out-of-band response in the strong $CO_2$ absorption spectral region.

Lifting the users' top pressure level to 0.005 hPa in the CRTM alpha version has also caused large errors in forward and Jacobian calculations for the High

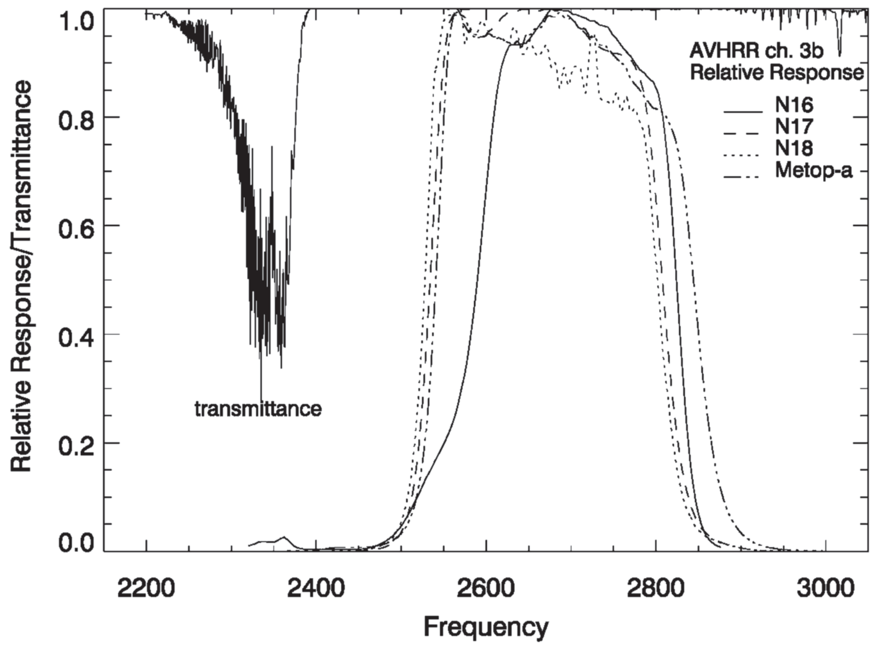


FIG. 2. Relative spectral responses of AVHRR channel 3b for *NOAA-16*, *NOAA-17*, *NOAA-18*, and *MetOp-A*. The black line is the transmittance between 0.005 (model top) and 20 hPa.

Resolution Infrared Radiation Sounder (HIRS) sounding channels. Unusually large Jacobians (derivatives with respect to atmospheric layers) have been reported to the CRTM team by HIRS users. This feedback, along with MICROS results reported here, has led to CRTM revisions in version 1.1. Analyses in this section suggest that the accuracy of forward modeling for AVHRR channel 3b on *NOAA-16* has significantly improved. The improvements to the accuracy of the Jacobians in CRTM v.1.1 are currently being validated.

## 3. Discussion and conclusions

The bias abnormality at *NOAA-16* AVHRR window channel 3b BT (see Fig. 1) only happens when all of the following three conditions occur simultaneously:

(i) out-of-band behavior,
(ii) user input top pressure is significantly higher than the CRTM model top pressure of 0.005 hPa, and
(iii) inaccurate treatment of such user input in the CRTM alpha version.

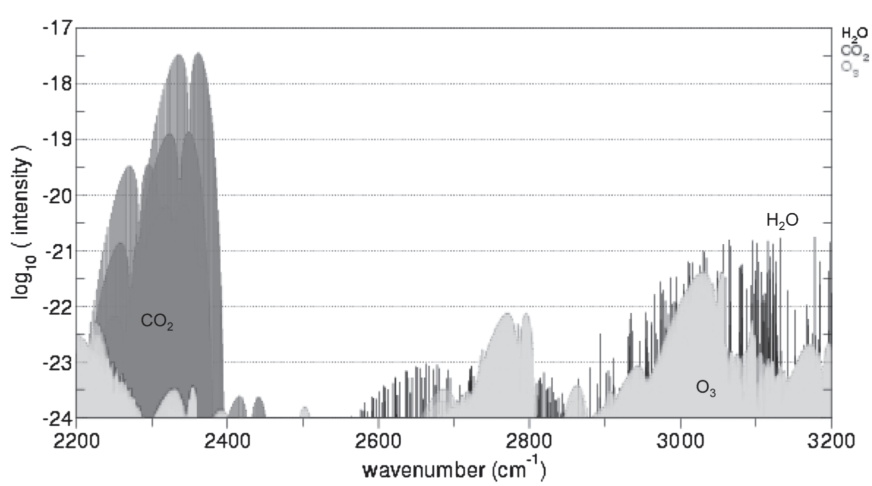


FIG. 3. Absorption line strengths of $CO_2$ (dark gray), $H_2O$ (black), and ozone (light gray) between 2200 and 3200 $cm^{-1}$. Data are from SpectralCalc.com.

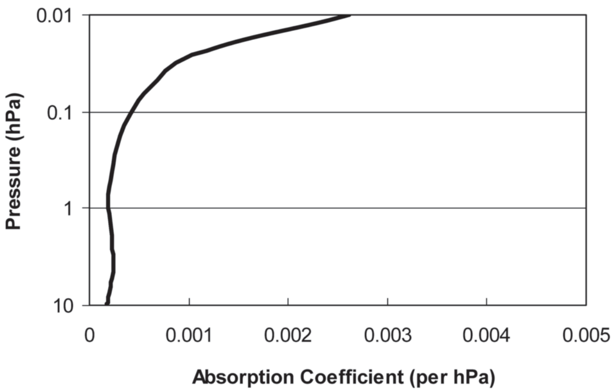


FIG. 4. Vertical distribution of absorption coefficients for *NOAA-16* AVHRR channel 3b.

The line-by-line radiative transfer calculation shows that the out-of-band directly depresses the channel 3b brightness temperature by 0.2 K for a midlatitude summer profile. Because the out-of-band response, the GFS input profile without extrapolation can cause significant error in the CRTM simulation.

Note also that Dash and Ignatov (2008) used Moderate Resolution Transmission 4.2 (MODTRAN4.2) model to calculate top-of-atmosphere (TOA) BTs. They also found that *NOAA-16* and *MetOp-A* AVHRR channel 3b brightness temperatures systematically differ more than 0.2 K. Analyses are currently underway to determine if similar mechanisms might be responsible for these anomalies.

Finally, we want to bring to attention that sensor characteristics, a radiative transfer model, and user expertise are important in radiance assimilations. In this note we quantitatively studied the out-of-band effect on *NOAA-16* AVHRR brightness temperature, which may bring the attention to engineers in building sensors. It is found that the peak of the out-of-band response for *NOAA-16* AVHRR channel 3b locates at the strong $CO_2$ absorption band near a wavenumber of 2350 $cm^{-1}$. The $CO_2$ absorption results in the sensitivity to atmospheric temperature at high altitudes. If the channel is used for determining sea surface temperature, a careful treatment is necessary for the atmospheric temperature increment at high altitudes in both retrievals and radiance assimilation. A stratospheric temperature profile is needed in the radiative transfer simulation, even though this channel is considered to be a window channel because of the out-of-band response. A proper model TOA height and a proper vertical resolution of the atmospheric profile are necessary for accurate radiance simulations. For atmospheric absorption of high nonlinearity, a fine vertical resolution of the atmospheric profile is required.

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